The contribution of radio echo sounding to the investigation of Cenozoic tectonics and glaciation in Antarctica

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The contribution of radio echo sounding to the investigation of Cenozoic tectonics and glaciation in Antarctica

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ABSTRACT. Continuous radio echo profiling of the ice/bedrock interface in Antarctica has been undertaken from an airborne platform by the Scott Polar Research Institute and the National Science Foundation of the United States during the austral summers of 1967–68 and 1969–70.

The method utilizes a pulse-modulated 35MHz radio sounding system having a resolution of 10 m in ice. The system is many times more rapid and is probably more accurate in deep polar ice than determinations of thickness by seismic shooting. The profiling technique has provided new evidence of the recent diastrophic and glacial history of Antarctica.

Radio echo soundings along the inland side of the Transantarctic Mountains from Victoria Land southwards to the Queen Maud Mountains confirm recent surface geological investigations and indicate a complex pattern of differentially tilted fault-blocks. Some of these blocks, possibly comprising Beacon Supergroup rocks, extend up to 600 km from the Ross Sea coast. Variations in the magnitude of tilting and secondary longitudinal and transverse faulting within the blocks combined with varying amounts of erosion have produced a complicated transitional zone between the epicratonic mountain belt and the lowland shield of the East Antarctic craton.

On the inland side of the mountains, valleys of probable glacial origin, but now submerged beneath the ice sheet, indicate that glaciers once descended both flanks of the Transantarctic Mountains. It is thought that these troughs, together with those at present penetrating the mountains, were eroded by local mountain glaciers during the mid-Cenozoic, following the initial uplift of the Transantarctic Mountain belt. With the onset of the full-scale continental glaciation the lower, inland sector became submerged by the progressive accumulation of ice in the interior. The present ice-flow pattern of the East Antarctic ice sheet is consequently discordant with much of the sub-glacial relief. This buried relief may have been little modified by recent cold-based ice.

CONTINUOUS radio echo sounding from aircraft has been developed in recent years by a team at the Scott Polar Research Institute (S.P.R.I.), Cambridge. It has made possible the rapid profiling of the ice/bedrock interface over vast areas of Antarctica (J. T. Bailey, S. Evans and G. de Q. Robin, 1964; Evans and Robin, 1966; Evans, 1967; Robin, C. W. M. Swithinbank and B. M. E. Smith, 1970; Robin *et al.*, 1970). The data used in this report were obtained during the austral summers of 1967–68 and 1969–70 by teams from the S.P.R.I. with the logistic support of the National Science Foundation (N.S.F.) of the United States. The author participated in the field during the 1969–70 Antarctic season but several other people have contributed substantially to obtaining the echo records used here, in terms of the development and operation of equipment.

Geomorphological interpretation of the data obtained from soundings inland of the Transantarctic Mountains between the Byrd Glacier and the Queen Maud Mountains reveal enough detail to evaluate and partially to reconstruct the sub-ice structure of this part of Antarctica. In addition, the detailed morphology of the sub-ice reflections provides details of the incipient stage of Antarctic glacierization.

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THE RADIO ECHO SOUNDING SYSTEM

Continuous radio echo profiling is not only more rapid but may surpass in accuracy conventional geophysical techniques, such as gravimetric and seismic methods (the former usually being tied to the latter), in determining depth to bedrock through cold, polar ice. This is primarily a result of the fact that both radio echo sounding and seismic shooting are sensitive, in contrasting ways, to temperature changes in the sounding medium. Robin (1958) and A. P. Crary (1963) have shown that, in Polar seismic exploration, cold ice ($> -30°$ to $-40°$C) can result in substantial noise from incoherent surface waves. The echoes then become extremely difficult to identify and to interpret. Many seismic results obtained on early traverses in East Antarctica suffered in this way and many of the seismograms showed no unambiguous reflections (C. R. Bentley, 1964).

The performance of radio echo sounding is also strongly dependent upon but inversely related to temperature (Robin, 1972). This is caused by increasing dielectric absorption per metre path length as ice temperatures approach the melting point. Laboratory experiments on ice obtained from a Greenland core show that losses at $-1°$C are approximately 0·05dB m^{-1} and 0·001dB m^{-1} at $-60°$C (Robin, Evans and Bailey, 1969). The performance of the system in respect of power losses by absorption is considerably better in the very cold ice of the East Antarctic plateau, just where seismic shooting encounters the greatest difficulties. Seismic refraction profiles, however, are still invaluable in providing information on velocity zonation in bedrock sections.

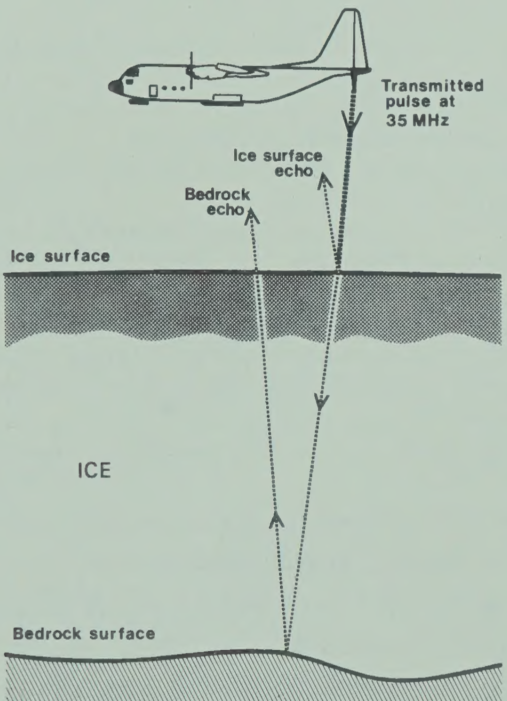

FIGURE 1. The Scott Polar Research Institute 35MHz, airborne radio echo sounding system. Electromagnetic energy is radiated downwards from antennae mounted in the tail of a U.S. Navy Hercules C-130B aircraft. The polar diagram indicates a beamwidth of 25° in the fore-and-aft direction and 10° in the transverse direction. Echo returns are obtained from ice/air, ice/rock, and ice/water interfaces

Description of the system

Similar to marine echo sounding techniques, the S.P.R.I. radio echo sounding system directs a pulse of transmitted energy downwards to the ice surface from an oversnow vehicle or an airborne platform (Fig. 1). The delay of the returning echo indicates the range to the reflecting surface (Fig. 2).

Radio frequencies between 30MHz and 500 MHz have been used since dielectric absorption increases very rapidly beyond 500MHz reaching 10dB per 100 m path length at 1000 MHz. The S.P.R.I. Mark IV system operates at 35 MHz and ranges in ice to an accuracy of 10 m can be resolved. Pulses returning from the ice surface and sub-ice reflectors are displayed on an intensity modulated cathode-ray tube (Fig. 2) and integrated on a single record by a continuously moving photographic film. Calibration marks are inserted electronically every minute and identified by an independent character string (see Figure 7 as an example).

Several factors have been shown to be important in the performance of radio echo sounding (Robin, Evans and Bailey, 1969): system performance (ratio of trans-

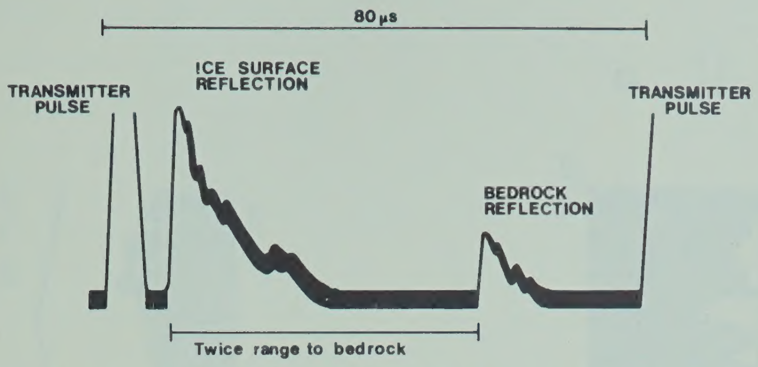

FIGURE 2. An A-scope display indicates salient features during ice-thickness measurements. The S.P.R.I. Mark IV System has a delay of 80 μs between transmitter pulse triggers. Returning reflections from ice or sub-ice surfaces are shown. The irregular echo tail results from scattering of energy over rough reflecting surfaces

mitted power to the minimum detectable power at the receiver); dielectric absorption of radio waves in ice; geometrical factors (size and configuration of the antennae, spreading of radio waves from a point and refraction effects at the snow surface) and finally reflection losses (ratio of incident energy to the reflected energy from the sub-ice surface). Calculations of echo strength have been made for several locations in Greenland and Antarctica (Robin, Swithinbank and Smith, 1970). They show that good echoes should be obtained over most of the Antarctic ice sheet excluding parts of Marie Byrd Land and the deepest areas of East Antarctica.

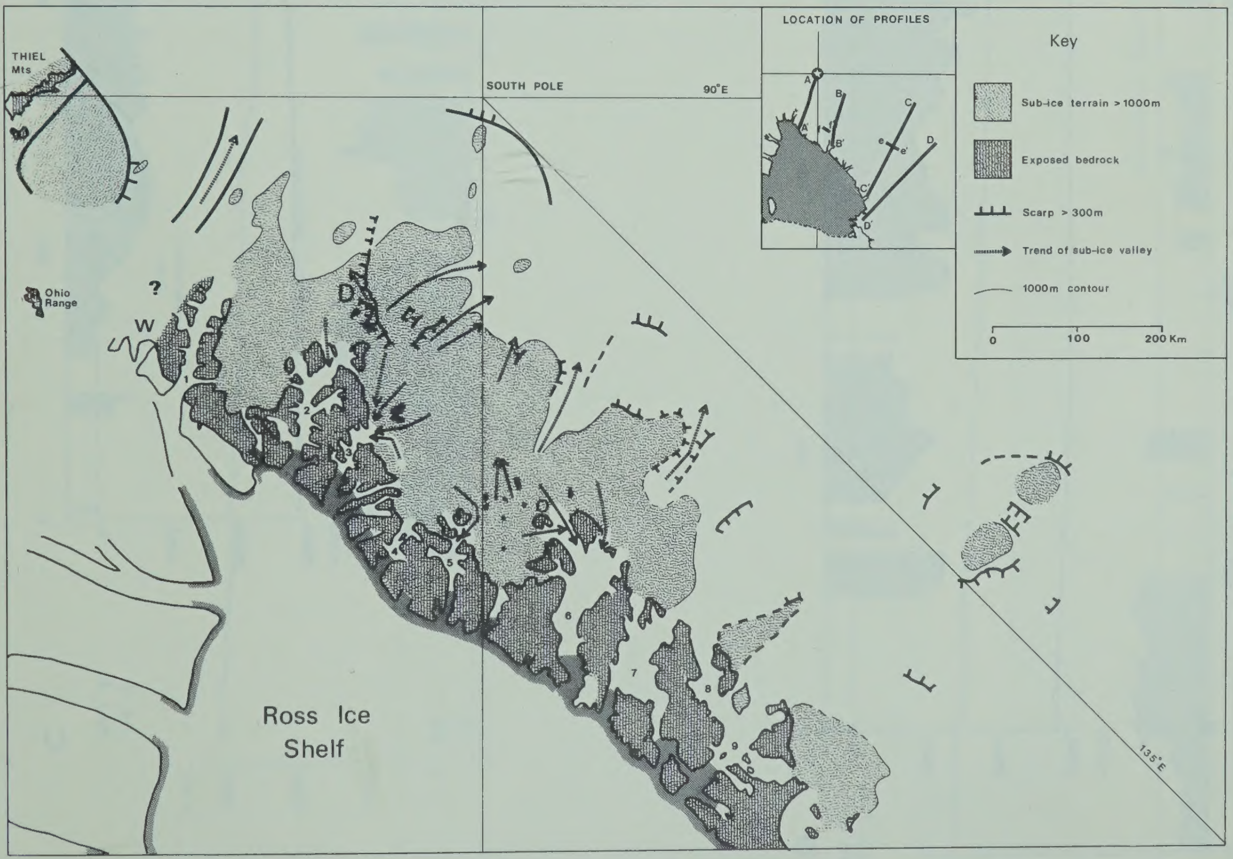

FIGURE 3. Sub-glacial structural elements between the southern Transantarctic Mountains and the South Polar plateau. Sub-glacial terrain above 1000m is indicated and the trend of sub-glacial valleys is shown. The numbered outlet glaciers are: 1. Reedy Glacier; 2. Robert Scott Glacier; 3. Amundsen Glacier; 4. Liv Glacier; 5. Shackleton Glacier; 6. Beardmore Glacier; 7. Lennox-King Glacier; 8. Marsh Glacier; 9. Nimrod Glacier. W = Wisconsin Range; D = D'Angelo Bluff; O = Otway Massif

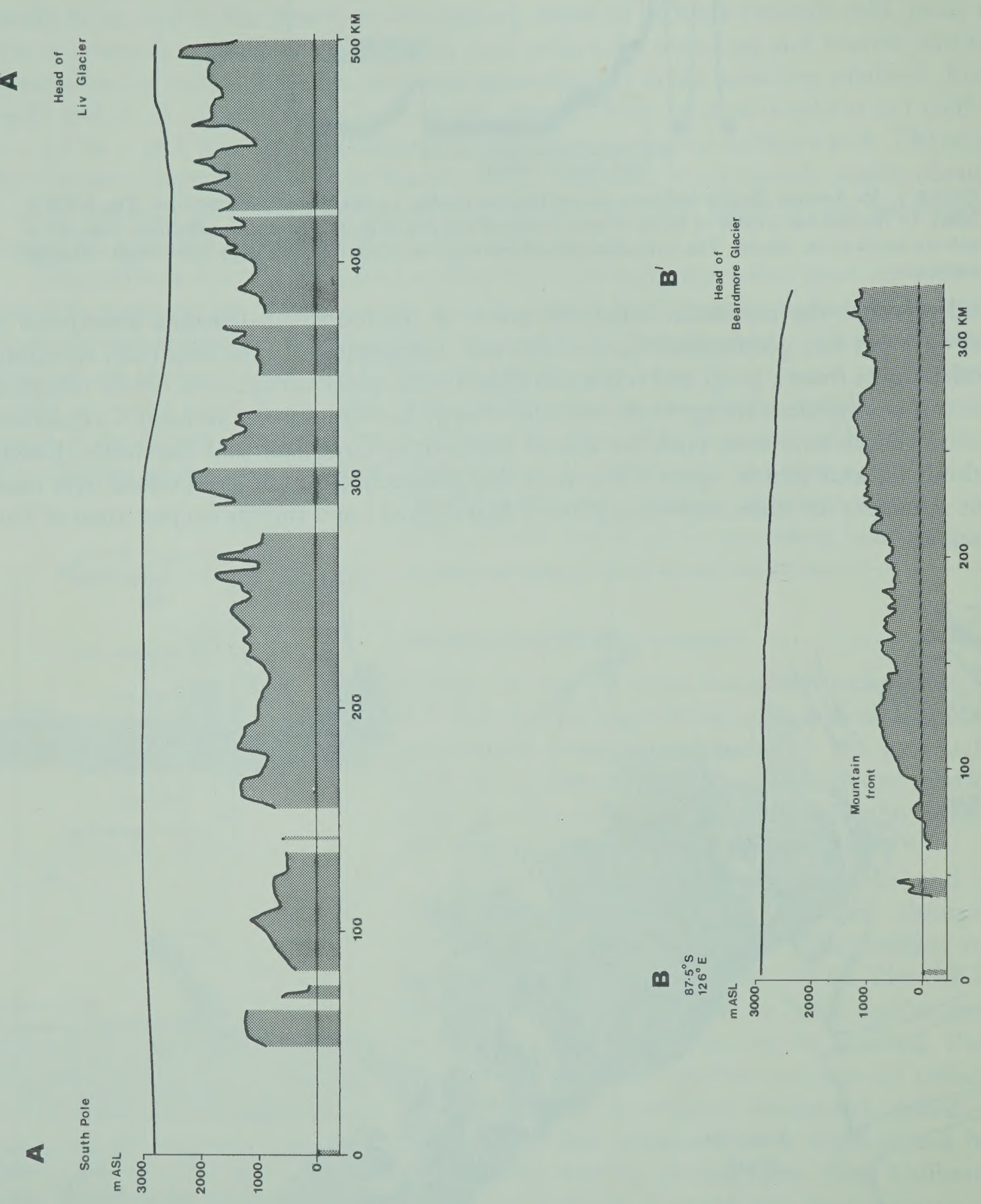

FIGURE 4. Real space profiles obtained by continuous radio echo sounding between the East Antarctic plateau and the Transantarctic Mountains. The location of the profiles is shown in Figure 3.

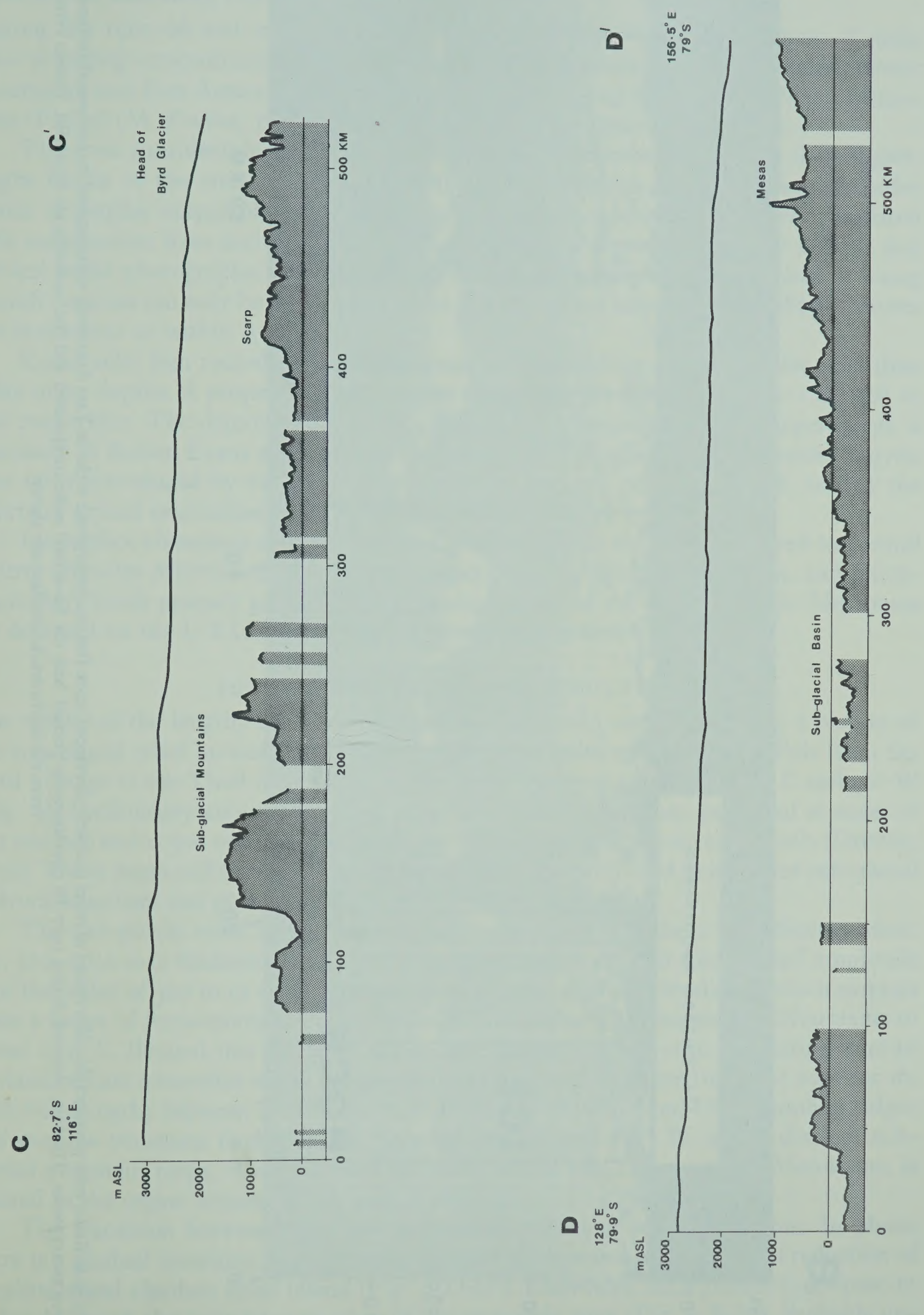

FIGURE 5. Real space profiles obtained by continuous radio echo sounding between the East Antarctic plateau and the Transantarctic Mountains. The location of the profiles is shown in Figure 3.

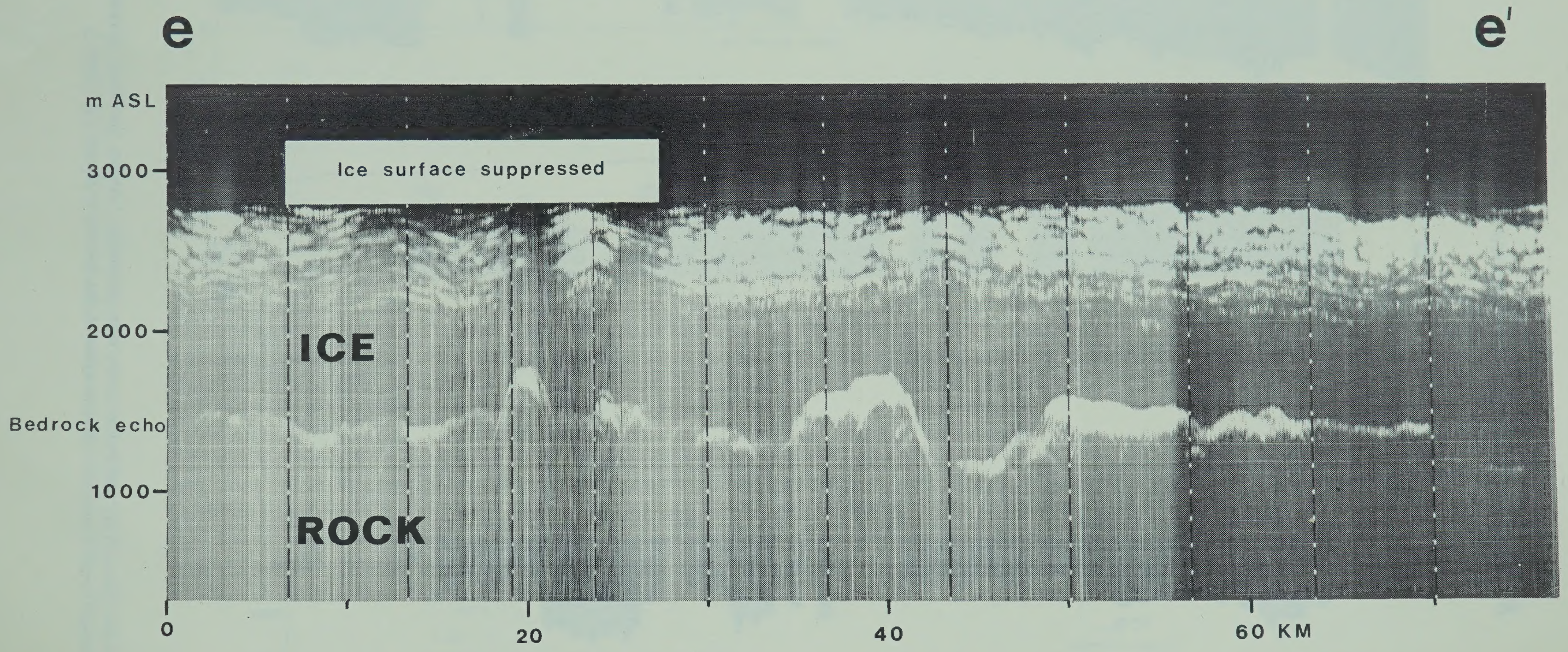

FIGURE 6. Radio echo photographic film record of relief probably developed upon Beacon Supergroup rocks in East Antarctica characterized by horizontal surfaces and steep escarpments. The film, obtained during 1967–68 operations, is printed with the horizontal scale compressed and the vertical scale expanded. Echoes returning from the ice/bedrock interface are shown

Operations and data reduction

During the 1967–68 and 1969–70 seasons, a joint S.P.R.I./N.S.F. programme of radio echo sounding concentrated several flights through and adjacent to the Transantarctic Mountains into East Antarctica, from southern Victoria Land to the Queen Maud Mountains (Fig. 3) (M. Forbes, 1968; Evans and Smith, 1970; Robin *et al.*, 1970).

There are considerable problems in analysing the results obtained during these flights. Flight tracks of the aircraft are obtained from the reduction of SFIM flight-recorder traces. A graphic output of aircraft track is produced by computer. The track is updated with independent fixes derived from the photogrammetrical resection of high oblique and vertical aerial photographs, obtained with a Trimetrogon System. This method of fixing aircraft position can only be undertaken when within sight of known topographical features but is accurate to within ±2 km.

Radio echo film records of ice thicknesses are reduced by converting the echo time delay to ice depths. A propagation velocity for radio waves in ice of 169 m μs^{-1} is used in this conversion. The determination of this value from laboratory and field experiments is discussed in Robin, Evans and Bailey (1969) and J. W. Clough and C. R. Bentley (1970). The error introduced by variations of temperature between 0°C and −60°C and by the effects of crystal orientation in an ice sheet is of the order of ±3 m μs^{-1}.

Ice-surface elevations are obtained from single airborne altimetry corrected to ground control altitudes determined by multiple altimetry during oversnow traverses, and photogrammetry (with primary ground survey) in the vicinity of the Transantarctic Mountains (as depicted on the U.S.G.S. 1 : 250 000 Reconnaissance Series Maps).

SUB-GLACIAL RELIEF AND STRUCTURE

The results of the lengthy data-handling process have been used to build up a picture of the sub-glacial relief between the Transantarctic Mountains and the South Pole from the Byrd Glacier to the Thiel Mountains, in the sector between longitude 145° E and 90° W (Fig. 3). Preliminary contour maps of sub-glacial relief have been produced at scales of 1 : 2 200 000 and 1 : 500 000, with contour intervals of 500 m and 300 m respectively (Drewry, 1972). These maps and details of radio echo profiles have been used to interpret sub-glacial bedrock structure and geomorphology.

The sub-glacial relief is complex but two major relief zones have been distinguished. Ice, 500–2000 m in thickness, covers an irregular mountainous area whose relief amplitude is of the order of 300 m to 1500 m (at 500 m to 2500 m above sea level) and which extends from a series of intra-montane embayments in the southern Transantarctic Mountains to about 145° E. Beyond this the other major zone is encountered—the undulating interior lowland of East Antarctica where the amplitude of the relief is reduced to about 200–400 m, with wavelengths between 4 and 6 km and at heights of 0–1000 m. High-standing ridges and outliers penetrate farther inland between 169° E and 140° W, and a discrete sub-glacial mountain range, divorced from the main belt of the Transantarctic Mountains, is located in the region around 88° S, 120° E (Fig. 3).

The transition between these two provinces appears to be very variable. In places there is a gradual transition from the mountains to the lowland with a gradual reduction of amplitude and absolute relief inland (Fig. 5, D-D′). Elsewhere, escarpments (300–1000 m in height) mark the inland termination of the mountain zone (Fig. 4, B-B′). Probable up-faulted outliers, beyond the transitional zone, exist as mountain blocks (Fig. 5, C-C′).

These variations are interpreted as a result of the differential inland tilting of tectonic fault-blocks which extend along the plateauward side of the Transantarctic Mountains. Such interpretations of the profiling data are considerably assisted by the remarkably well-developed structural control of relief in the mountains, which has resulted, where it has been determined in the exposed sectors, from a combination of Mid- to Late Tertiary block faulting and extensive intrusion by dolerite bodies into a thick (3000 m) sub-horizontal sedimentary sequence—the Beacon Supergroup (P. J. Barrett *et al.*, 1972). The exposed relief is, in consequence, dominated by structural benches, mesas, tablelands and single and multiple escarpments (V. R. McGregor, 1963).

It is thought that the rocks of the Beacon Supergroup succession extend well out into East Antarctica, up to 600 km from the Ross Sea coast at latitude 82°30′ S. Here radio echo evidence indicates that there are scarp-terminated, near-horizontal surfaces developed in bedrock with little surface relief and cut by steep-walled valleys (Fig. 6), indicative of Beacon rocks. Interpretation of the meagre magnetic evidence available also suggests that a sedimentary section exists in this area, although it is probably only thin (E. S. Robinson, 1962). In this case the Beacon succession has probably been preserved by vertical uplift of the strata in the form of outlying mountain ranges shown in Figures 3 and 5 (C-C′).

In other areas the Beacon rocks extend into East Antarctica where the fault-blocks of the Transantarctic Mountains are gently tilted inland and hence outcrop as large ridges. This is the case between the Queen Maud Mountains and the South Pole. A crustal block is tilted a few degrees to the south-west and extends from the head of the Robert Scott Glacier to about 88°30′ S. It also dies out laterally beyond the 180° meridian. The fault-block has a steep scarp face (1000–1500 m high) on its northern and eastern margins (shown in Figure 3 adjacent to D). D'Angelo Bluff appears as a small exposed section of the northern block-edge. Parts of the upland reach over 2000 m in height, but in places the surface comprises a regular tableland at 1800 m with surface relief less than 100 m in amplitude (Drewry, 1972; Fig. 4), and probably reflects structural control by the Beacon Supergroup. Near the South Pole, seismic refraction profiles indicate an upper layer in which the velocities for the compressional wave (3·5 to 4·5 km s^{-1}) were interpreted as passing through sedimentary strata or frozen till (Robinson, 1964; Clough and Bentley, 1972). In view of the attitude and morphology of the bedrock in this region (Fig. 4, AA′), a sedimentary interpretation is preferred. The absence of steep magnetic anomalies further suggests the presence of a thin sedimentary rock layer (Robinson, 1962).

In general terms it appears that a simple tectonic model for the inland flank of the Transantarctic Mountains, such as the faulted horst of T. W. E. David and R. E. Priestley (1914), G. T. Taylor (1930), R. W. Fairbridge (1952) and R. L. Nichols (1966, 1969), can no longer be admitted. The exposed and the sub-glacial relief indicate that there has been a main axis of uplift along a coastal (eastern) fault producing a series of major crustal blocks which are tilted inland (McGregor and A. F. Wade, 1969). In some cases the magnitude of vertical uplift and degree of tilting leads to a gradual reduction of absolute relief towards the interior. In others, where the strata may have been less severely tilted, more uplifted or suffered less denudation, steep escarpments characterize the transitional zone.

GLACIAL INVESTIGATIONS

Investigation in areas adjacent to the present-day exposed Transantarctic Mountains has helped to elucidate the history and mode of glacial activity in the mountain zone.

Radio echo records have indicated the presence of sub-glacial valleys in this area. They appear to be of two types. There are those which are tributary to existing outlet glaciers (for example, Reedy, Robert Scott, Amundsen, Liv, Shackleton and Beardmore Glaciers) and which extend the bedrock networks of these glaciers (Fig. 3). The second type of valley consists of those channels which are entirely sub-glacial, independent of the outlet systems, and which drain in an inland direction (Fig. 3). These valleys appear to be distributed on the plateauward side of several upland blocks beneath the ice sheet. Figure 7 shows a radio echo photograph across three of these valley features, in this case flanked by nunataks. The origin of these valleys is thought to be glacial for the following reasons:

(1) The shape of the valley in cross-section is similar to the morphometry of known glaciated valleys. The shape of the sides of the left-hand valley in Figure 7 is approximated by the following equations:

$$y = 6{\cdot}988 \times 10^{-7}\, x^{2{\cdot}273} \text{ (right flank)}$$
$$y = 4{\cdot}307 \times 10^{-4}\, x^{1{\cdot}629} \text{ (left flank)}$$

H. Svensson (1959) found that an exponent, $n \approx 2$ ($n = 2$ represents a regular parabola) fitted certain glacial valleys in Sweden. W. L. Graf (1970) has given values of n between 1·6 and 2·0 for curves fitted to glaciated valleys in the U.S.A. The much smaller pre-exponent constant for the Antarctic case reflects its greater width.

(2) The long profile of the major trough south-west of the Otway Massif extends for at least 100 km and has an average gradient of 0·9° to 1·0°. Deglaciated valleys of similar dimensions in the northern hemisphere possess similar gradients (for example, Yosemite: length 140 km; mean gradient 1·1°).

(3) The regional location of these valleys indicates that they originate in highland zones of the Transantarctic Mountains known to have been the source of early local glaciation (J. H. Mercer, 1968a—Reedy Glacier area; Mercer, 1972—Beardmore region).

The existence of inland-oriented sub-glacial valley networks has several implications. The valleys, whatever their origin (fluvial or glacial), must be related to a drainage system older than the continental ice sheet in East Antarctica. If they are glacial, and more detailed reduction by deconvolution techniques (C. H. Harrison, 1970) may further assist in determining the character and origin of these features, then they may be related to an early, mountain phase of glacierization. In such circumstances, temperate valley glaciers and small local ice caps with basal ice temperatures at the pressure melting point and with abundant free-water in the melt season, would have been capable of substantial erosion. Such an epoch of intense local glacial erosion has been suggested elsewhere in the Transantarctic Mountains. G. H. Denton *et al.* (1969, 1970) consider that the ice-free areas of southern Victoria Land were actively eroded by temperate, wet-based glaciers more than 4 million years ago. Mercer (1968a) found that by early Pleistocene times most of the erosive sequences in the Wisconsin Range had ended. Further investigations by Mercer (1972) in the Beardmore Glacier area indicate a similar early phase of intense glacial erosion.

The continental ice sheet developed from the lengthening and thickening of these inland-flowing glaciers. Once the growing ice sheet had developed sufficiently steep surface gradients the ice-flow pattern would have been drastically modified, the inland-trending valleys being submerged by the seaward-moving ice sheet. A change in the thermal régime of the ice cap must have accompanied this accumulation, basal ice temperatures falling progressively to below the pressure melting point.

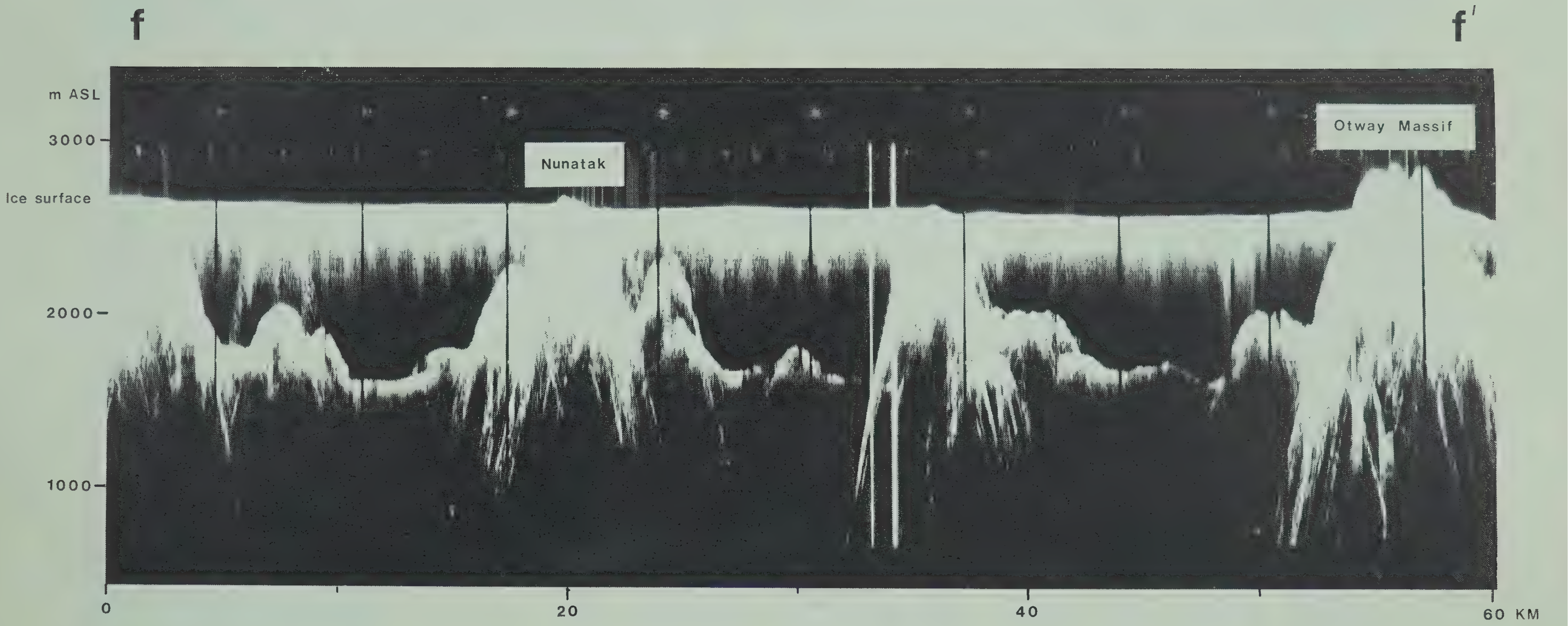

FIGURE 7. Radio echo photographic film (1969–70 season) along profile f—f′. Sub-glacial valleys are shown separated, in this case, by nunataks. The intense brightening on the film immediately below the ice surface represents scattering of energy from an irregular surface (rough reflector). In rugged terrain, separate echoes may arise from favourable localities (e.g. surfaces of gentle curvature). They are viewed over a wide range of angles in the fore-and-aft direction as the aircraft passes. Thus the range travels through a minimum and the echo traces a characteristic shape on the record, approximately hyperbolic in outline. Such hyperbolas appearing on the records do not, however, represent realistic slopes or surfaces, especially along their trailing edges. In the central valley (above), the hyperbolic echoes below the surface and near the nunatak are probably side-echoes generated by other surface peaks, but at a greater range and to one side of the flight-path

A corollary to such a sequence of events would be that the early erosional relief was little modified during the later stages of glacierization. Indeed present-day glaciological investigations (C. R. Wilson and Crary, 1961; Bentley, 1962; M. B. Giovinetto *et al.*, 1966; E. S. Robinson, 1966) show that ice flow from the plateau to the Ross Ice Shelf is small and that between the South Pole and the Queen Maud Mountains calculated basal shear stresses are low ($0{\cdot}2$ to $0{\cdot}4 \times 10^5$ N m^{-2}: from W. F. Budd *et al.*, 1971) and calculated basal ice temperatures approximately $-10°$ to $-20°$C (ibid.). This confirms the view that the cold-based and localized ice flow in this region is unlikely to have achieved much effective erosion.

A further implication of radio echo findings is that there must have been a highland zone substantial enough to develop drainage systems and provide local centres for permanent snow accumulation (i.e., a proto-Transantarctic Mountain belt adjacent to the open water of the Ross Sea). In accordance with recent estimates for the initiation of glaciation in Antarctica (J. D. Hays and N. D. Opdyke, 1967; S. V. Margolis and J. P. Kennett, 1971; R. H. Rutford *et al.*, 1968; W. E. LeMasurier, 1972) such a highland must date from at least the Mid-Tertiary. Although a proto-Transantarctic Mountain belt has been implied in previous investigations (C. Bull *et al.*, 1962; Mercer, 1968a, 1968b; P. E. Calkin and R. L. Nichols, 1972) the new evidence of plateauward drainage pre-dating the ice sheet and effecting considerable erosion, strengthens the argument against the alternative chronology proposed by G. W. Grindley (1967). He suggests that in pre-glacial times the Transantarctic Mountains did not exist as a mountain barrier but as a 'subdued plateau landscape' (p. 562) over which the interior continental ice subsequently spread cutting the First Glacial Surface in the Miller Range at the head of Nimrod Glacier. The present elevated character of the mountains is attributed by Grindley to a response in the mantle to ice loading in the interior of East Antarctica which caused the marginal zone of the continent to rise. Mercer (1972) has shown that there has been some tectonic dislocation to early till sequences which indicates that glaciation probably commenced upon a surface undergoing the final stages of epeirogenic uplift. Whether in later stages movement was continued in response to ice loading is unconfirmed but possible.

These tentative concepts of diastrophic and glacial interaction may thus provide further evidence of the denudational history of the Transantarctic Mountains. If this belt is essentially a Mid-Tertiary relief feature and was rapidly submerged beneath an expanding ice sheet, then the primary relief elements of the mountains are tectonic and glacial. Any pre-glacial phase of sub-aerial erosion must in consequence have been extremely restricted or even absent (a hypothesis suggested by David and Priestley in 1914 and reiterated more recently by B. M. Gunn and G. Warren, 1962). Further investigations based on sub-glacial data may help to resolve these fundamental problems.

CONCLUSIONS

(1) Airborne radio echo sounding techniques now provide a rapid method of continuously profiling the ice-bedrock interface over large areas of Antarctica. (2) Radio echo soundings have indicated that the sub-glacial structural configuration inland of the Transantarctic Mountains is considerably more complex than previously envisaged. Steep scarps are found in some localities at the transition between the mountainous province and the lowland continental shield. In other areas the mountains become progressively lower and die out gradually towards the interior. Further complications are generated by discrete up-faulted

blocks or massifs found up to 600 km from the coast yet structurally part of the mountain zone.

(3) A general model for the tectonic framework of the Transantarctic Mountains is proposed in which there has been a main axis of uplift along a coastal fault producing a series of major crustal blocks which are tilted inland. Variations in tilting, faulting, igneous intrusion and subsequent erosion have produced the complex transition into East Antarctica.

(4) Evidence has been presented to suggest that Beacon Supergroup rocks may extend as far as 135° E (600 km from the Ross Sea coast at latitude 82°30′ S), confirming suggestions that the northern plainland fringe of the East Antarctic plate may comprise thin layers of sedimentary strata overlying the basement complex (A. P. Kapitsa, 1960).

(5) Radio echo soundings have indicated a pattern of sub-glacial valleys, some of which extend the bedrock network of present-day outlet glaciers in the Transantarctic Mountains. Others, however, with inland orientations are attributed to an early Mid-Tertiary mountain glacier phase. Such inland-flowing glaciers must have been, in part, responsible for the initial accumulation of the continental ice sheet but subsequent reversal of ice flow has submerged these valleys which appear to have been little modified by the restricted and cold seaward ice flow.

ACKNOWLEDGEMENTS

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Résumé. *La contribution des sondages par radio à l'investigation des tectoniques du cénozoique et de la glaciation en Antarctique.* Le Scott Polar Research Institute et la U.S. National Science Foundation ont entrepris un sondage par radio continuel de la ligne de démarcation entre la glace et le socle rocheux en Antarctique depuis une station aérienne pendant l'été austral de 1967-68 et celui de 1969–70. On a utilisé un système de sondage radio à 35 MHz ayant une résolution de 10m dans la glace. Ce système est beaucoup plus rapide et probablement plus exact dans la glace polaire profonde que les déterminations d'épaisseur par sondages seismiques. La technique de profil a donné de nouvelles preuves de la récente histoire diastrophique et glaciaire de l'Antarctique. Les sondages par radio le long du côté intérieur des Montagnes Transantarctiques depuis Terre Victoria et vers le sud jusqu'aux montagnes de la Reine Maud confirment de récentes investigations géologiques sur la surface, et indiquent un motif complexe de blocs causés par des failles et inclinés de façons différentes. Quelques-uns de ces blocs, comprenant probablement de roches du « Beacon Supergroup », s'étendent plus de 600 km depuis la côte de la mer de Ross. Des variations dans l'amplitude d'inclinaison, et des failles secondaires longitudinales et transversales à l'intérieur des blocs, combinées avec de probables différences spatiales dans l'érosion, ont produit une zone transitoire compliquée entre la ceinture montagneuse epicratonique et les plaines du bouclier du craton de l'antarctique orientale. Sur le côté intérieur des montagnes, des vallées probablement d'origine glaciaire, mais maintenant gisant sous la glace, indiquent que des glaciers ont descendu les deux flancs des Montagnes transantarctiques. On considère que ces vallées, et aussi celles qui pénètrent les montagnes aujourd'hui, sont dues à la glaciation locale des montagnes pendant le mi-cénozoique, et sont la conséquence du soulèvement initial de la ceinture des Montagnes Transantarctiques. Au commencement de la grande glaciation continentale, le secteur des basses terres intérieures fut submergé par entassement progressif de la glace dans l'intérieur. Le système de drainage actuel dans l'Inlandsis oriental n'est conséquemment pas en accord avec la plupart du relief sub-glaciaire. Il est possible qu'il se soit produit de petites modifications dans cette topographie enselevie dues à la glace à base froide plus récente.

FIG. 1. On peut voir le système 35MHz de sondage par radio et par air du Scott Polar Research Institute sur l'illustration ci-dessus. L'énergie électromagnétique rayonne vers le bas à partir d'antennes montées dans la queue d'un avion U.S. Navy Hercules C-130B. Le diagramme polaire indique une largeur de rayon de 25° de l'avant à l'arrière et de 10° transversalement. Des retours d'écho sont obtenus à partir de la ligne de démarcation entre des moyens de permitivité contrastés: glace/air; glace/roche ou glace/eau

FIG. 2. Un arrangement « A-scope » indique les traits saillants pendant la mesure de l'épaisseur de la glace. Le système S.P.R.I. Mark IV a un délai de 80 μs entre les pouls transmis. On peut voir des réflections retournant des surfaces glaciaires ou sous-glaciaires. La traine irrégulière de l'écho est causée par le dispersement de l'énergie sur des surfaces réflectives qui ne sont pas lisses

FIG. 3. Des éléments morphostructurels sous-glaciaires entre les Montagnes Transantarctiques du su det le plateau du pôle sud. Le terrain sous-glaciaire au dessus de 1000m au dessus du niveau de la mer est indiqué et on peut voir la direction des vallées sous-glaciaires. Les langues glaciaires externes numerotées sont: 1) glacier Reedy, 2) glacier Robert Scott, 3) glacier Amundsen, 4) glacier Liv, 5) glacier Shackleton, 6) glacier Beardmore, 7) glacier Lennox-King, 8) glacier Marsh, 9) glacier Nimrod. W = montagnes Wisconsin, D = D'Angelo Bluff, O = Otway Massif

FIG. 4 & 5. Des profils obtenus par sondage par radio continuel entre le plateau de l'Antarctique oriental et les Montagnes transantarctiques. L'emplacement des profils est montré sur la Fig. 3

FIG. 6. Enrégistrement photographique filmé de sondage par radio de la topographie qui se développe probablement sur les roches du « Beacon Supergroup » dans l'Antarctique oriental et caracterisée par des surfaces horizontales et des escarpements raides. Le film, réalisé pendant les opérations de 1967–68, est imprimé avec l'échelle horizontale compressée et l'échelle verticale élargie. On y montre des échos retournant de la ligne de démarcation entre la glace et le socle rocheux

FIG. 7. Film photographique de sondage par radio (saison 1969–70) le long du profil (f–f′). Des vallées sous la glace se montrent séparés, dans ce cas, par des nunataks. L'éclairement intense du film immédiatement sous la surface de la glace représente l'éparpillement de l'énergie à partir d'une surface irrégulière (une réflecteur qui n'est pas lisse). Sur un terrain rugeux, des échos séparés peuvent provenir d'endroits favorables (ex. des surfaces doucement courbées). On peut les observer sous une grande variété d'angles de l'avant à l'arrière au moment où passe l'avion, et l'écho trace une forme caractéristique sur l'enrégistrement, approximativement hyperbolique. De telles hyperboles apparaissant sur les enrégistrements ne représentent pas des pentes ou des surfaces réalistes, surtout vers l'arrière. Dans la vallée centrale (en dessus) les échos hyperboliques, sous la surface, près du nunatak, sont probablement des échos secondaires, engendrés par des pics d'une autre surface, mais avec une plus grande ampleur, en dehors du chemin de vol

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ZUSAMMENFASSUNG. *Der Beitrag des Radio-Echolotungens zu der Erforschung des Känozoikum-Tektoniks und der Vergletscherung in der Antarktis.* Das Scott Polar Research Institute und die U.S. National Science Foundation haben während den südlichen Sommern 1967–68 und 1969–70 ein im Flugzeug eingebautes Radio-Echolotungssystem verwendet, um ununterbrochene Profile der Grenze zwischen Eis und Felsgrund in der Antarktis zu bekommen. Es wird ein 35 MHz Radio-Echolot mit Impuls-Amplitudenmodulation und mit Auflösung von 10m in Eis verwendet. In dem tiefen Polareis ist dieses System sehr viel schneller, und wohl auch genauer, als seismische Eisdickemessungen. Diese Profilierenstechnik hat neue Beweise über die neuzeitliche diastrophische und glaziale Geschichte der Antarktis verschafft. Radio-Echolotungen, welche die inländische Seite des Transantarktischen Gebirges entlang, südwärts von Victoria-Land bis zu dem Königin-Maud-Gebirge, durchgeführt worden sind, bestätigen vor kurzem an der Oberfläche unternommene geologische Untersuchungen, und deuten auf eine komplexe Struktur von verschieden geneigten verschobenen Schollen hin. Einige dieser Schollen, welche vielleicht Felsen der ‚Beacon-Supergroup‘ einschliessen, reichen bis 600km von der Küste des Ross-Meeres. Variationen in der Grösse der Neigungen und Sekundärverwerfungen in longitudinaler und transversaler Richtung innerhalb der Schollen, zusammen mit wahrscheinlichen räumlichen Unterschieden in der Erosion, haben eine verwickelte Übergangszone zwischen der epikrationischen Gebirgskette und dem flachen Schild des ostantarktischen Kratons verursacht. An der inländischen Seite der Berge weisen Täler von wahrscheinlich glazialer Herkunft, welche nun aber unter der Eiskalotte liegen, darauf hin, dass sich Gletscher vormals an beiden Seiten des Transantarktischen Gebirges weiterbewegten. Man nimmt an, dass diese Vertiefungen, zusammen mit denen die sich gegenwärtig auf den Bergen befinden, auf lokale Gebirgsvergletscherung während dem mittleren Känozoikum zurückzuführen sind, und der anfänglichen Erhebung des Transantarktischen Gebirges nachfolgten. Am Anfang der grossen kontinentalen Vergletscherung wurde der niedrigere inländische Sektor von progressiver Aufhäufung von Eis im Inneren überschwemmt. Das gegenwärtige Eisentleerungssystem des Inlandeises der Ostantarktis stimmt daher mit der Struktur des unterglazialen Reliefs im allgemeinen nicht überein. Diese unterglaziale Topographie ist vielleicht von neuerem kaltbasiertem Eis ein wenig verändert worden.

ABB. 1. Das im Flugzeug eingebaute Scott Polar Research Institute 35MHz Radio-Echolotungssystem wird hier gezeigt. Elektromagnetische Energie wird von Antennen im Heck eines U.S. Navy Hercules C-130B Flugzeugs nach unten ausgestrahlt. Das polare Diagramm zeigt eine Strahlenbreite von 25° in Kiellinie und 10° in transversaler Richtung. Echos werden von Grenzflächen zwischen Medien von kontrastierender Durchlässigkeit (Eis/Luft; Eis/Fels oder Eis/Wasser) zurückgeworfen

ABB. 2. Eine "A-Scope" Ausstellung zeigt hervorragende Merkmale im Laufe der Eisdickemessungen. Das S.P.R.I. Mark IV System hat eine Verzögerung von 80 μs zwischen Senderpulsen. Zurückstrahlungen von der Oberfläche vom Eis oder von unterglazialen Flächen werden gezeigt. Der unregelmässige Echoschweif resultiert aus Streuung der Energie über unebenen Reflexionsflächen

ABB. 3. Unterglaziale morphostrukturelle Elemente zwischen dem südlichen Transantarktischen Gebirge und dem südpolaren Plateau. Unterglaziales Terrain mehr als 1000m über dem Meeresspiegel und die allgemeine Richtung der unterglazialen Täler werden gezeigt. Die numerierten Gletscherströme sind: 1) Reedy-Gletscher, 2) Robert-Scott-Gletscher, 3) Amundsen-Gletscher, 4) Liv-Gletscher, 5) Shackleton-Gletscher, 6) Beardmore-Gletscher, 7) Lennox-King-Gletscher, 8) Marsh-Gletscher, 9) Nimrod-Gletscher. W = Wisconsin-Geb., D = D'Angelo-Bluff, O = Otway-Massif

ABB. 4 & 5. Profile, die durch ununterbrochene Radio-Echolotungen zwischen dem ostantarktischen Plateau und dem Transantarktischen Gebirge erhalten worden sind. Die Lage der Profile ist in Abb. 3 gezeigt

ABB. 6. Radio-Echo-Film der Topographie, die wohl auf Felsen der ‚Beacon-Supergroup‘ in der Ostantarktis entstand, und welche für ihre horizontalen Oberflächen und steilen Landstufen charakteristisch ist. Der Film, der während den Forschungsarbeiten von 1967–68 entstanden ist, wurde mit verkleinertem horizontalen Massstab und mit vergrössertem vertikalen Massstab abgezogen. Er zeigt Echos, die von der Grenzfläche zwischen Eis und Felsboden zurückstrahlen

ABB. 7. Radio-Echo-Film (Saison 1969–70) dem Profil (f–f′) entlang. Man sieht, dass die unterglazialen Täler in diesem Falle von Nunataks getrennt sind. Die intensive Aufhellung auf dem Film, die unmittelbar unter der Eisoberfläche sichtbar ist, stellt Streuung der Energie von einer unebenen Reflexionsoberfläche dar. In unebenem Terrain kann man von günstigen Orten (z.B. von Oberflächen mit leichter Welligkeit) verschiedene Echos bekommen. Wenn das Flugzeug vorbeifliegt werden sie von vielen Aspekten in Kiellinie gesehen, und das Echo zeichnet auf den Film eine charakteristische Gestalt, die ungefähr hyperbolisch in der Kontur ist. Solche Hyperbeln auf dem Film bedeuten aber nicht realistische Neigungen oder Flächen, besonders an der Hinterkante. Die hyperbolischen Echos in dem mittleren Tal (oben), unter der Oberfläche und neben dem Nunatak, sind wohl Seitenechos, von anderen, aber weiteren Spitzen, an der Oberfläche und zur Seite des Flugwegs, verursacht

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